

Mesh Generation Challenges: A Commercial Software Perspective

AIAA-2017-3790

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- CAD Interoperability and Access to Geometry
- Mesh Adaptation & High-Order Mesh Generation
- Mesh Generation Kernels
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Introduction

Introduction

- Numerical simulation of complex flowfields about realistic aircraft configurations has advanced rapidly over the last several decades.
- The NASA CFD Vision 2030 Study provides an assessment of the current state of the art CFD and provides insight into requirements decades into the future.
- Mesh generation is a key enabling component in the simulation environment.
 - The mesh generation process is very applied, very practical.
 - Much of it is done interactively using commercial tools that have evolved over decades in response to user demands.

Introduction

- As a commercial software vendor, the focus of research and development is customer driven.
- Some aspects of the NASA study pertain to capabilities that are needed near-term, like CAD Interoperability. Other aspects are more long term concerns, like automated mesh generation in parallel.
- Commercial vendors need to ensure their investment dollars address the forecast of the NASA Study in a responsible way to meet the customer needs.
- The investments of commercial vendors should be coordinated with academia and government.
- The presentation will focus on 4 topics:
 1. CAD interoperability and access to geometry
 2. Mesh adaptation and high-order mesh generation
 3. Mesh generation kernels in a parallel setting
 4. Automated mesh generation.

CAD Interoperability and Access to Geometry

CAD Interoperability

- Concurrent engineering and outsourcing has elevated the importance of efficient product data exchange.
- Mechanical CAD (MCAD) models are built to define the geometry from a manufacturing perspective. They contain more information than needed for CFD applications.
- They have issues with representation, finite tolerances and translation.
- The effect of these issues are amplified in mesh generation for CFD.
- Mesh generation from MCAD models is less robust, requiring additional user involvement and less repeatability, leading to increased design study uncertainty.

CAD Interoperability

- There is a need for separation of CAD topology and mesh topology.
 - CAD topology is constructed to minimize geometry error.
 - Mesh topology aims to minimize solution error.
- Pre-CAD or CAE models are often created through simplification and de-featuring of MCAD models.
- Perhaps a combination of Pre-CAD, which includes a conceptual design parametric space, and MCAD data should be considered.
- The parametric space would be used to construct the mesh topology while the mesh would lie on the geometrically accurate MCAD model.

Access to Geometry

- Geometry access has always been a requirement in the mesh generation process.
 - Initially geometry was simple, such as cubes, spheres, cylinders, etc.
 - More elaborate shapes were represented by discrete geometry (2D network of points or triangles).
- Many commercial mesh generation tools allow for import of native CAD or common formats, such as IGES and STEP
- Internally the geometry is used to place boundaries of the mesh on the defined geometric surfaces.
- Once the mesh is made and output the access to the geometry is lost.

Access to Geometry

- Geometry should be persistent throughout the CFD simulation process if the goal is to:
 - Perform mesh adaptation.
 - Elevate linear meshes to high order.
 - Perform design optimization through shape change.
- This requires a CAD kernel beyond the initial mesh creation phase.
 - The kernel must be lightweight and provide optimal querying capabilities.
 - It does not need the full functionality to create geometry. Leave that to the CAD vendors.
- Pointwise is developing an API to a lightweight version of the geometry kernel in Pointwise.
 - Geode is a 4th generation B-Rep solid modeling kernel.
 - The lightweight kernel is Geode Core.
 - Full querying capability with limited creation capability.
 - Currently in private beta with selected partners and customers. Planning for public beta is underway.

Access to Geometry

- There is still a disconnect between the output mesh and the geometry.
- Currently Pointwise supports over 60 mesh output formats and permits users to output the geometry in a proprietary file format. Users can also write a plugin for their own mesh format.
- A strategy (or schema) is needed to provide the geometry associativity in a compact, efficient manner.
- The schema needs to be flexible to accommodate different mesh file formats and modes of specifying boundary conditions.
- The downstream mesh data typically only knows about user-labeled body parts, not the underlying mesh entities.

Access to Geometry

- Downstream mesh operation will need to refer to lower level mesh entities, such as edges, triangle and quadrilateral surface elements and individual points.
- The schema must provide the translation from the boundary conditions to the lower level mesh entities.
- Then translate from these mesh entities to the geometry entities in the IGES, STEP or other geometry file.
- Then there the question of “Who owns the mesh?”. The geometry API or the flow solver application calling it.

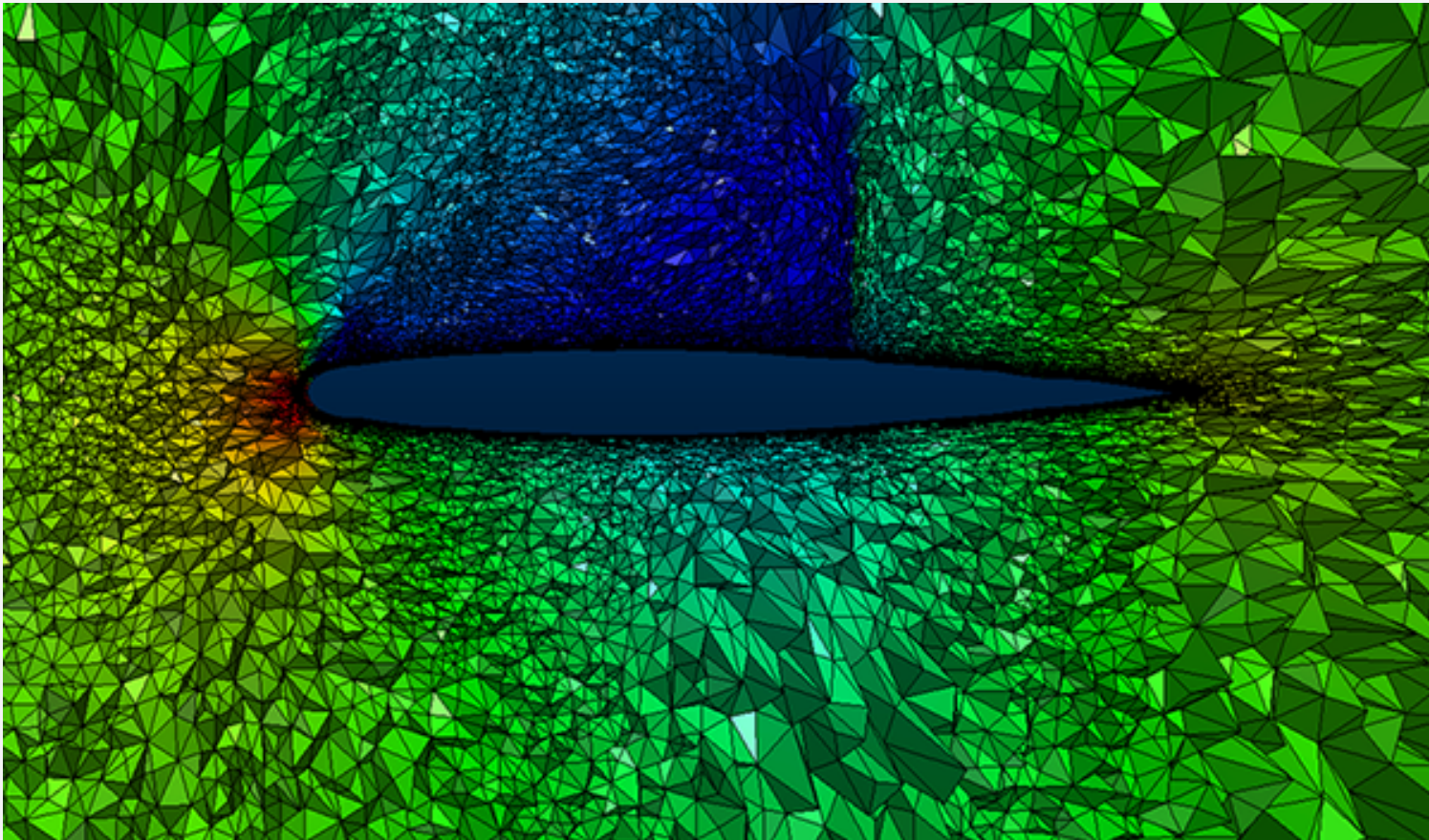
Mesh Adaptation & High-Order Mesh Generation

Mesh Adaptation

- For a fully automated CFD process the mesh must be adaptable as the solution evolves.
 - A priori mesh generation is nothing more than an educated guess at the discretization requirements.
 - Best practices are followed that have evolved over years of experience, but optimal meshes are still elusive.
 - Errors in the solution are only known once a solution is attempted.
- A significant amount of research in mesh adaptation has been performed in recent years.
 - Feature-based methods use truncation errors or estimate errors by computing gradients of scalar fields, such as pressure, density or velocity magnitude.
 - Adjoint-based methods solve auxiliary equations to get sensitivity of mesh changes to desired output functional, such as lift or drag.

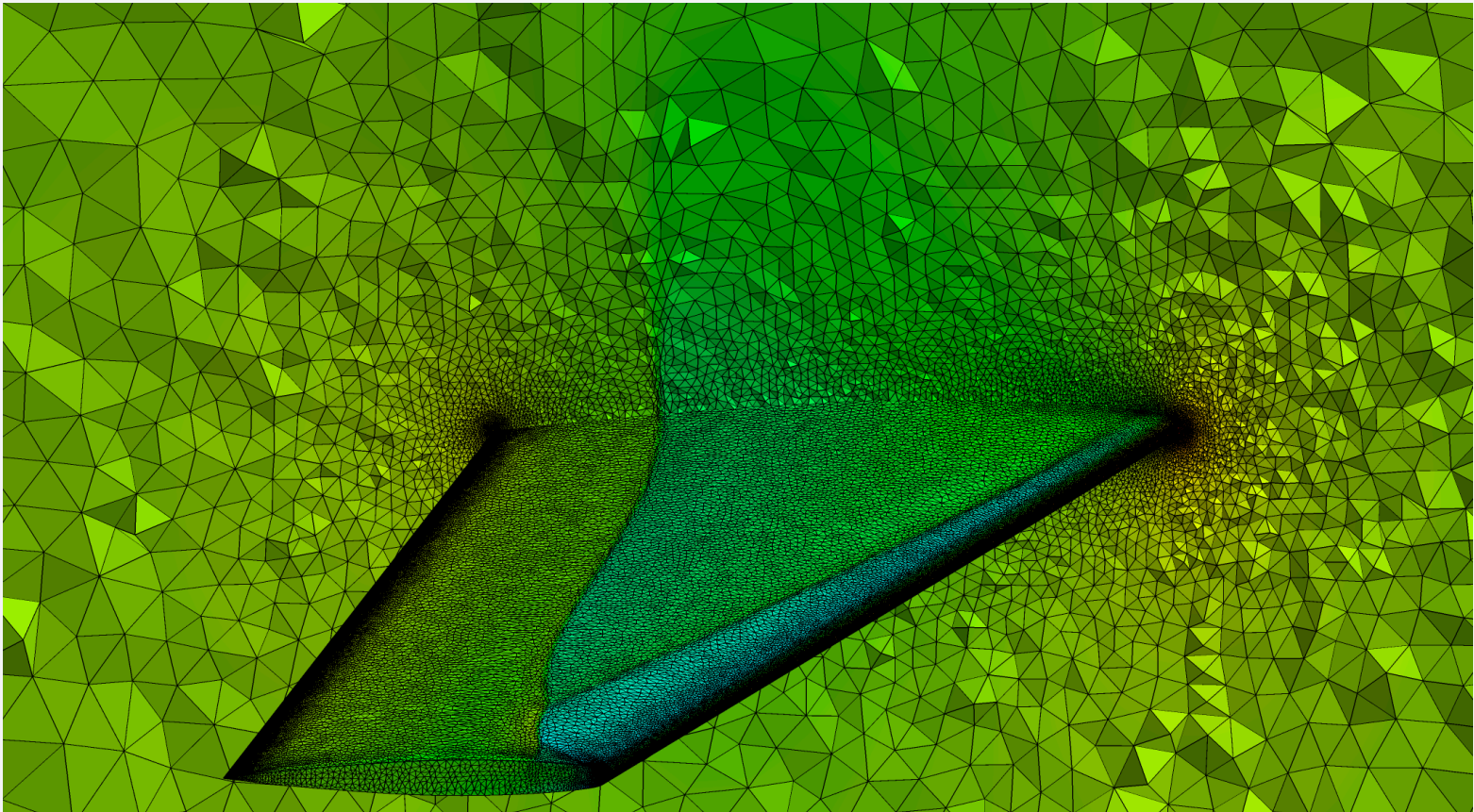
Mesh Adaptation

- Onera M6: adaptively refined for viscous solution. (AIAA-2017-3109)
- Adjoint based adaptation in FUN3D with Pointwise.



Mesh Adaptation

- Onera M6: adaptive repositioning of nodes for inviscid solution. (AIAA-2015-2038)
- Feature-based adaptation with Weighted Condition Number Smoothing.

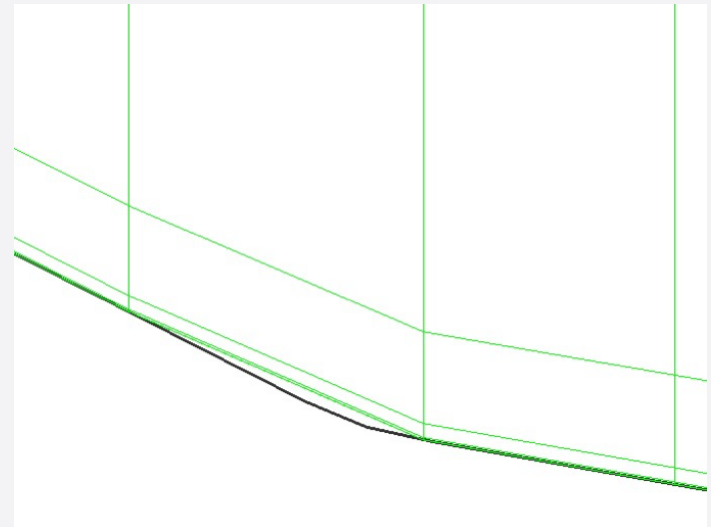
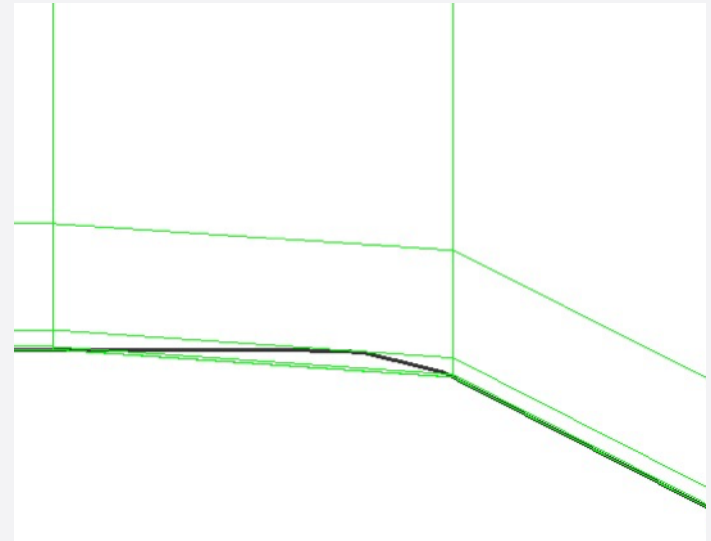


Mesh Adaptation

- Key component is the spacing field. Once known then refinement/coarsening or repositioning can proceed.
- Many times the refinement/coarsening process performed by the flow solver is a simplified version of the initial mesh process.
 - Simple cell subdivision: Element quality tends to decrease with each refinement.
 - Connectivity modification can improve quality.
 - Full version of tetrahedral mesh scheme not available or restricted for robustness reasons.
 - Refining of prismatic meshes is problematic.
 - Element max-included angles can easily approach 180 degrees.
 - Refining the stack of prisms identically can succeed.

Mesh Adaptation

- Boundary refinement brings geometry back into the picture.
- Simple point projections can recover true shape.
- Convex curvature in the surface normal direction can cause element inversion.
- Concave curvature can cause poorly shape or distorted elements.
- Interior mesh smoothing is often needed to ensure mesh quality.



Mesh Adaptation

- In general, mesh adaptation is more complicated than simply subdividing edges and elements.
- It probably requires access to geometry.
- It may require complex mesh operations, such as connectivity optimization via edge and face flips.
- It might be better served with access to full mesh generation techniques, such as Delaunay schemes and mesh extrusion methods.
- And it could require mesh smoothing that is robust to ensure valid meshes are produced.

Mesh Adaptation

- In an HPC environment the adaptation modules must be parallel and thread-safe.
- The partitioning requirements for the mesh may differ from flow solver.
- Transfer of data between mesh and flow solver must be compact and must allow for repartitioning on the fly.
- The frequency of mesh-solver interactions will depend on the application.
 - A limited number for steady-state analyses
 - Many more for unsteady analyses.

High-Order Mesh Generation

- Finite Element Methods (FEM) have been evolving in recent years.
- Whether Discontinuous Galerkin (DG) or Continuous Galerkin (CG), they can now handle complicated physics, including shocks and discontinuities.
- Higher order is achieved by incorporating more nodes on and inside each element.
- Near boundaries these elements can curve to match the boundary shape.
- Viscous boundary elements can become highly curved.

High-Order Mesh Generation

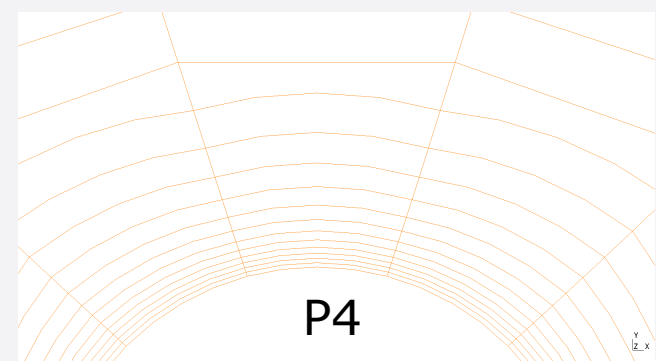
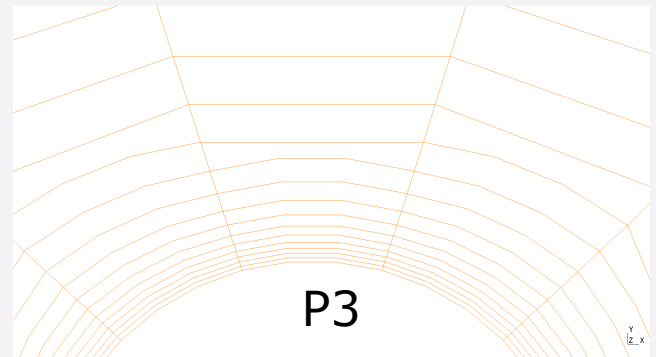
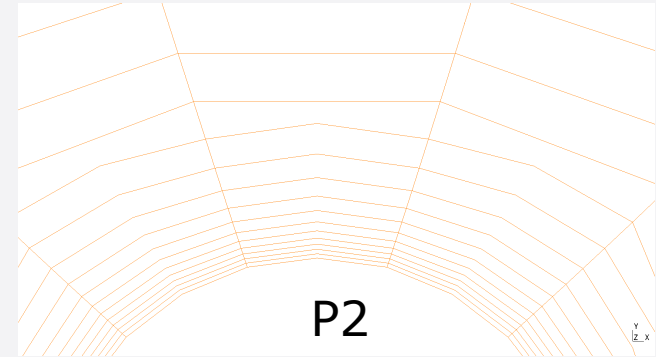
- Generating curved meshes from the beginning is not currently possible in commercial mesh generation codes.
- Some research has been performed where the extrusion process will produce curved meshes. (AIAA-2016-1673, AIAA-2017-0584).
- It is also possible to define the entire mesh as curved using spline surfaces throughout.
- These are popular in computer graphics and very high order ALE applications, such as blast waves.

High-Order Mesh Generation

- Most FEM practitioners modify linear meshes.
- High Order Preprocessor (HOPR) is open source and can import linear structured block meshes and agglomerate elements to form curved hexahedral meshes.
- Researchers at Barcelona Supercomputing Center (BCS) and MIT propose a method using a measure of distortion in a smoothing method.
- Fortunato and Persson apply unstructured Winslow smoothing using FEM to curve linear meshes.

High-Order Mesh Generation

- Karman-Shoemaker is elevating meshes to high order and then constructs splines to curve boundary edges and any internal edge that needs curving.
- After elevating edges, the internal edge nodes are placed using Bezier splines or linear interpolation, depending on the edge orientation.
- The original corners and the edge nodes form serendipity elements, from which the internal nodes are constructed from interpolation.
- Curving proceeds from the boundaries and stops when the next layer is not tangled.
- 3-D has been demonstrated for simple case.

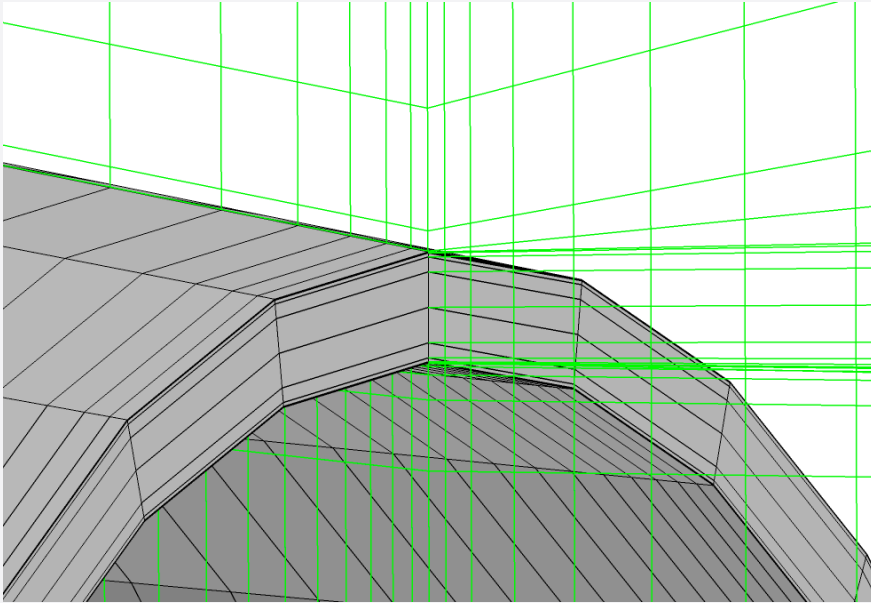


High-Order Mesh Generation

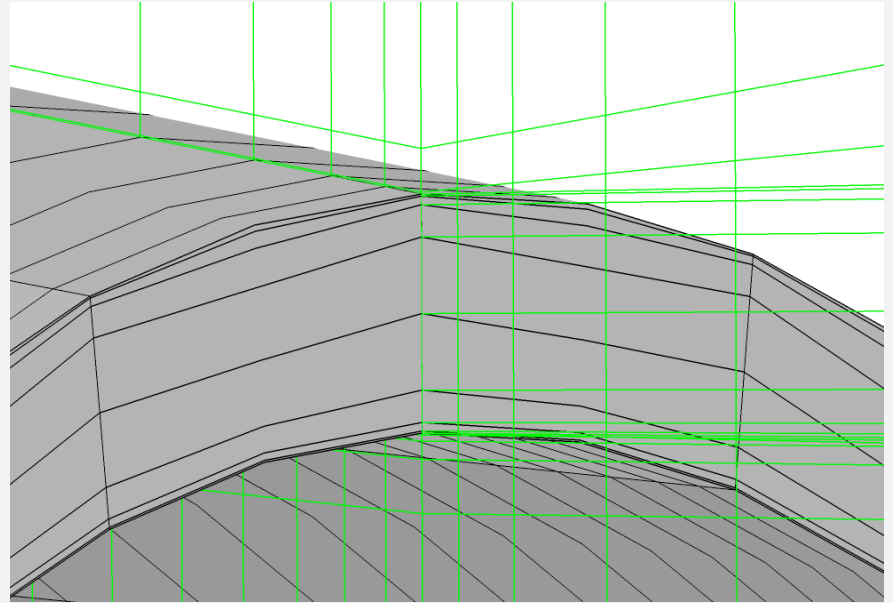
- Elevating linear volume meshes to higher polynomial degree is relatively straightforward for flat geometries or meshes without viscous clustering.
- Curved boundaries complicate the process.
- The process includes:
 - 1) Elevate each element by adding internal edge, face and element nodes.
 - 2) Place new boundary nodes on the true surface.
 - 3) Optionally curve the surface nodes.
 - 4) Smooth the internal nodes.

High-Order Mesh Generation

- Surface smoothing is sometimes required when there is high curvature in the surface tangential direction.



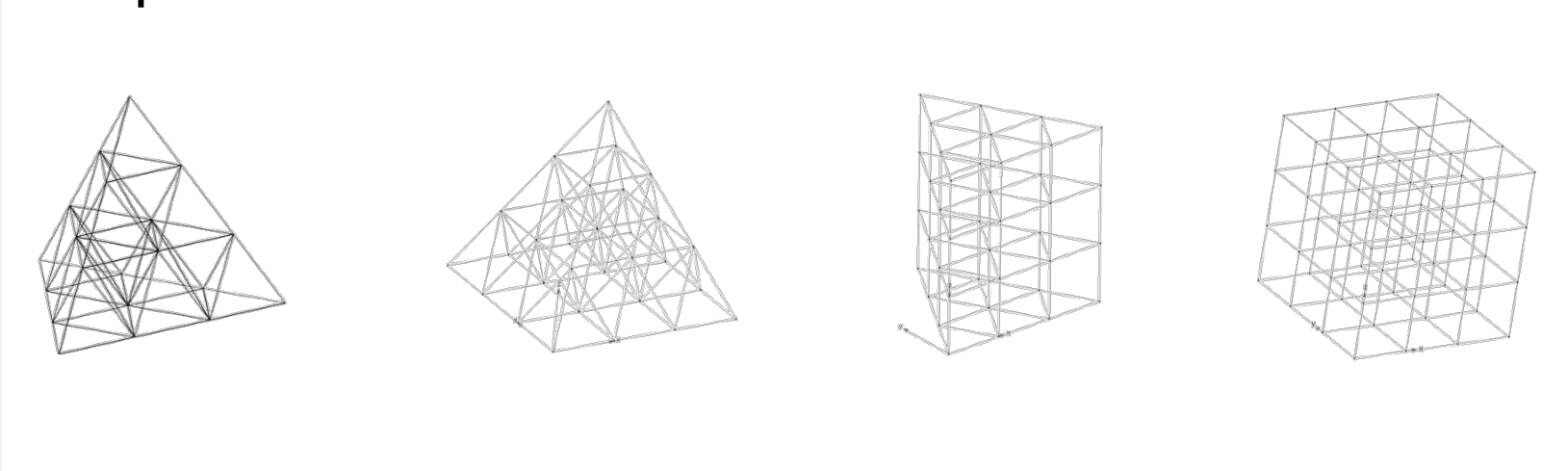
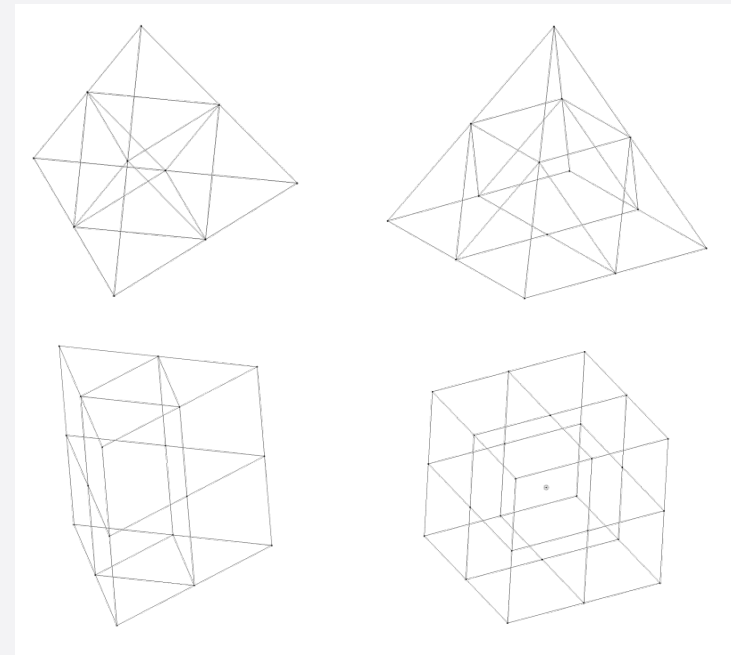
Linear surface mesh



P2 surface mesh

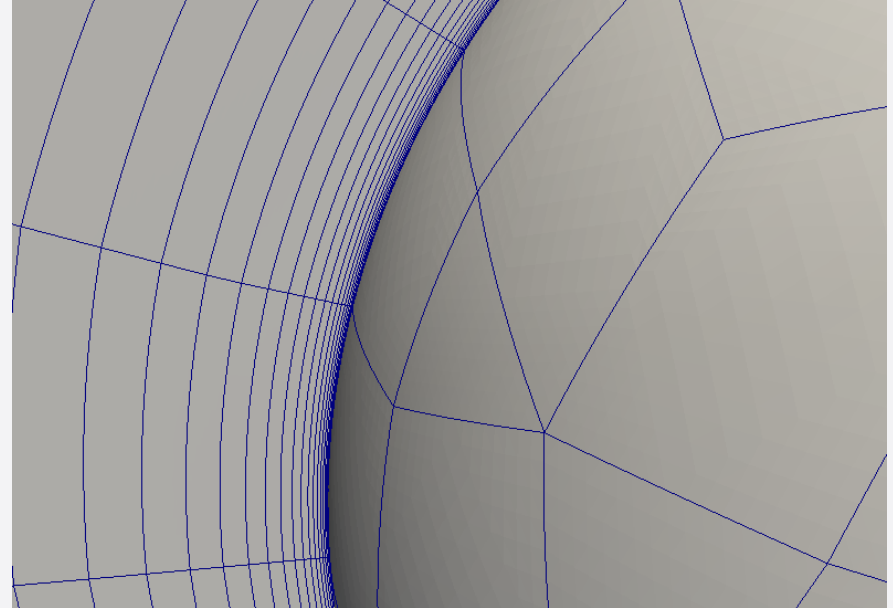
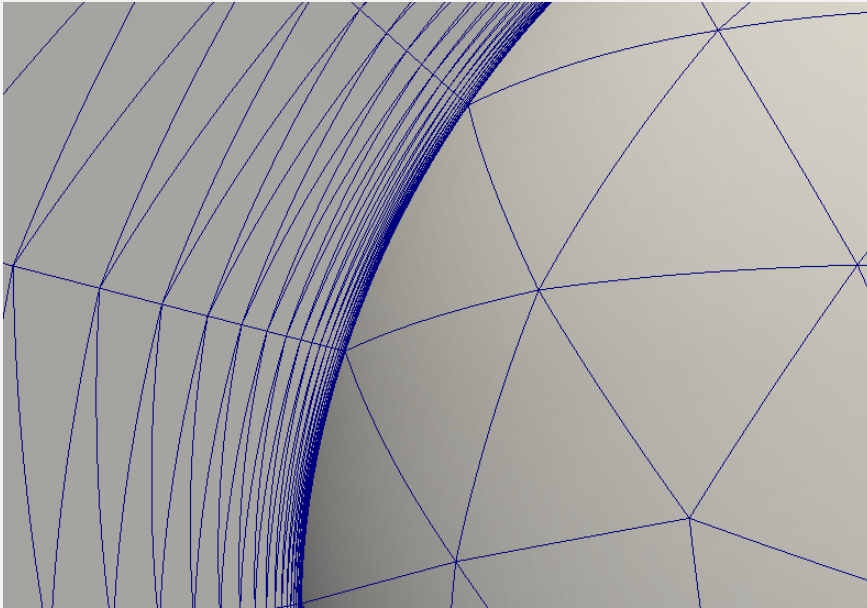
High-Order Mesh Generation

- Karman et. al. described a curving process in (AIAA-2016-3178).
- Mixed element meshes were elevated to P2, P3 and P4.
- WCN Smoothing is used to ensure valid meshes are produced.



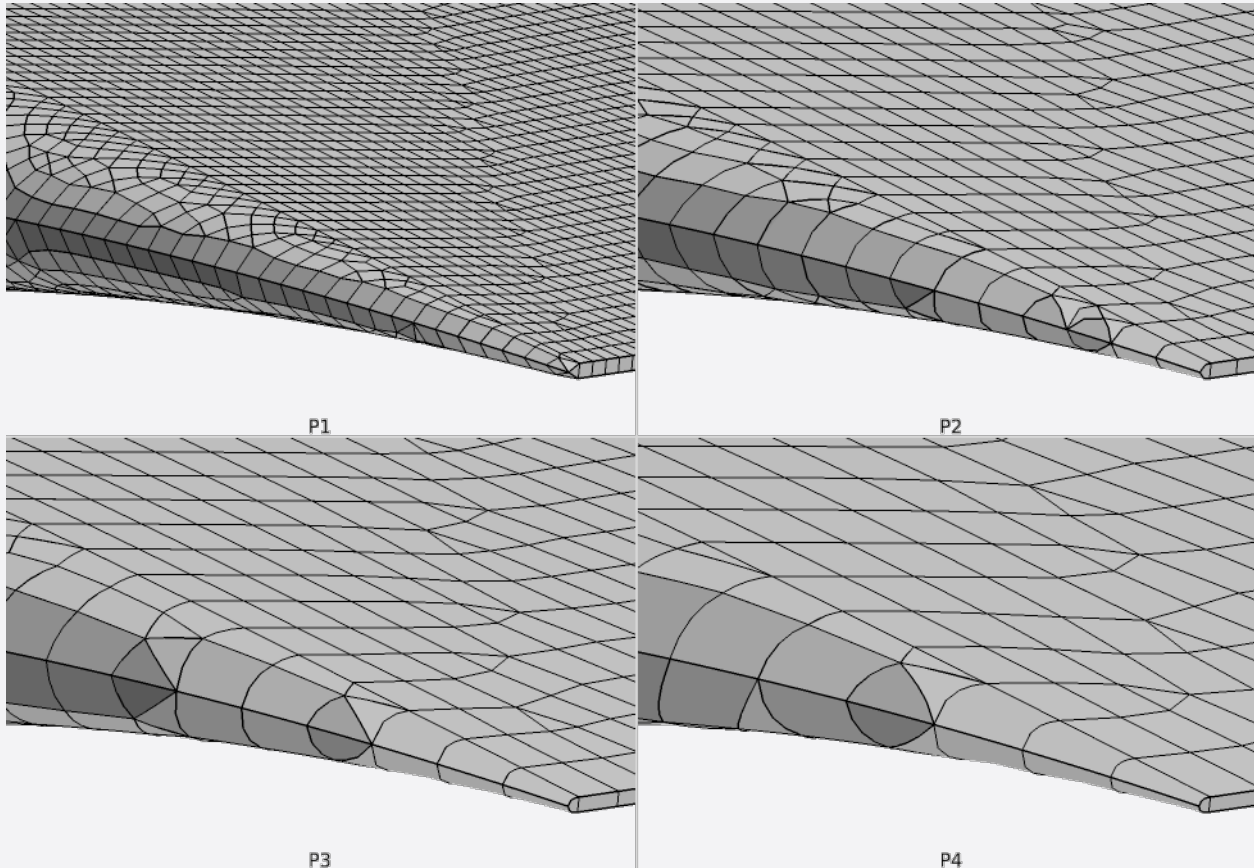
High-Order Mesh Generation

- Sphere mesh for all-tet and mixed element meshes.
- Paraview used to display the curved mesh.



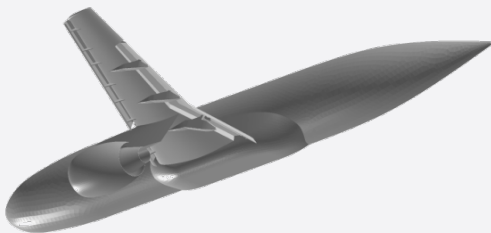
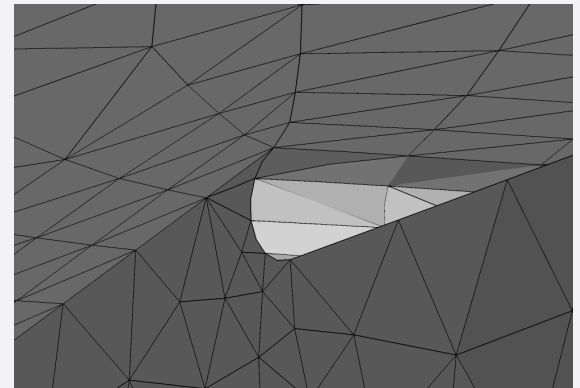
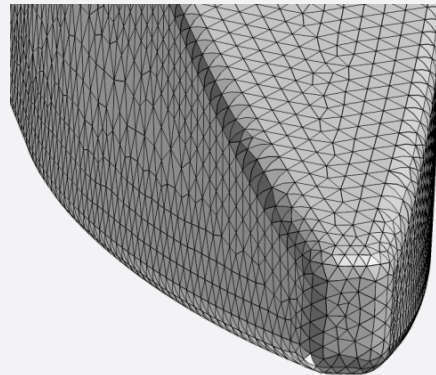
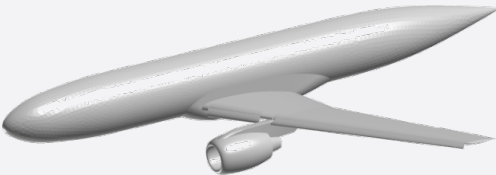
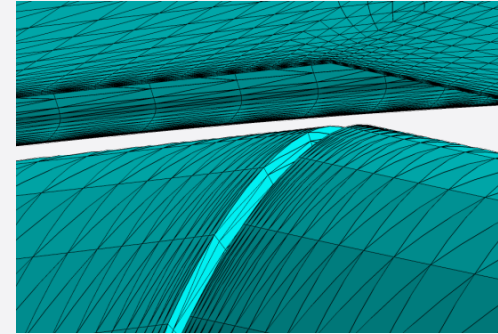
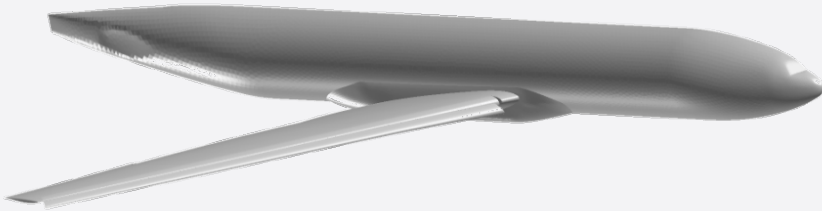
High-Order Mesh Generation

- Onera M6 mesh series created for P1 – P4.
- FieldView used to display meshes as arbitrary polyhedra.



High-Order Mesh Generation

- HL-CRM and JAXA configurations from HiLiftPW-3 elevated to high order.



H- and P- Adaptation

- Most efficient approach will involve h- and p-adaptation.
 - Regions with discontinuities in geometry or solution are better suited for h- adaptation.
 - Smooth regions can be handled using p-adaptation.
- To perform h-p adaptation properly the flow solver and mesh generator need to work together. This will enable the full set of mesh modification operations, instead of a subset.
- Efficient two way communication is needed, especially in an HPC environment where repartitioning may play a role.

Mesh Generation Kernels

Mesh Generation Kernels

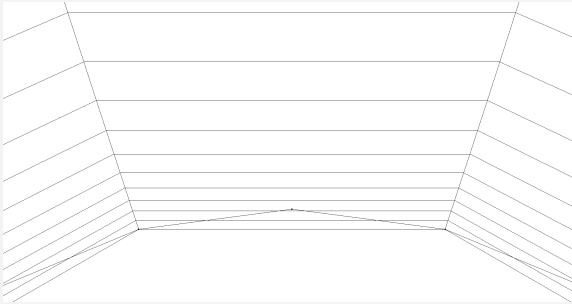
- The NASA study requires a hands-off, automated process in an HPC setting.
- This requires modular thread-safe mesh kernels.
- The more prominent kernels are:
 - Mesh smoothing: Needed for multiple applications.
 - Normal viscous extrusion: May provide most robust approach to automated viscous meshing.
 - Hexahedral dominant volume mesh generation: Highly automated approach to volume meshing. Less applicable to viscous meshing alone.
 - Delaunay mesh generation: Needed for multiple applications.

Mesh Smoothing

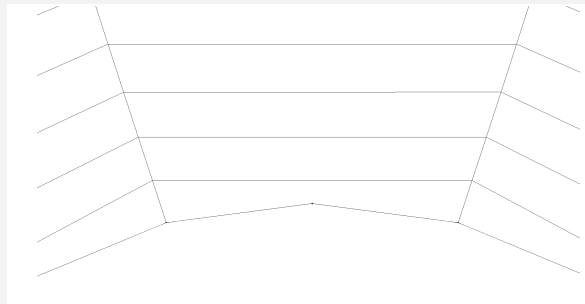
- Spring Analogy – Simple. Can use tension and/or torsional springs. Does not guarantee valid mesh.
- Linear-Elastic – Most common method applied to adaptation and high-order meshing. Only works when boundaries are moving. Young's Modulus or Poisson's Ratio modified to impose stiffness in regions with tight clustering.
- Winslow Elliptic Smoothing – Common in structured meshing. Difficult in unstructured due to lack of valid global computational mesh. FEM implementation by Fortunato and Persson is promising for high-order curving.
- WCN Smoothing – Provides most robust approach to complex geometry problems. Recent advances support all element types with defined viscous clustering.

Mesh Smoothing

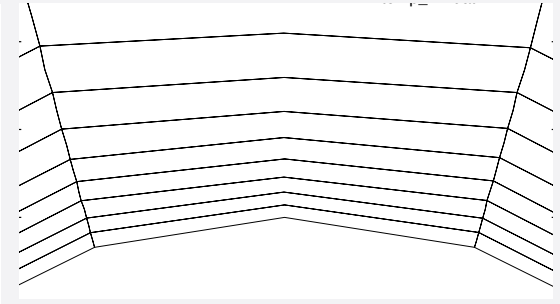
- L-E smoothing applied to tightly clustered meshes can be problematic.
- Isotropic material properties can cause viscous spacing to be altered.



Linear clustered mesh without boundary elevated.



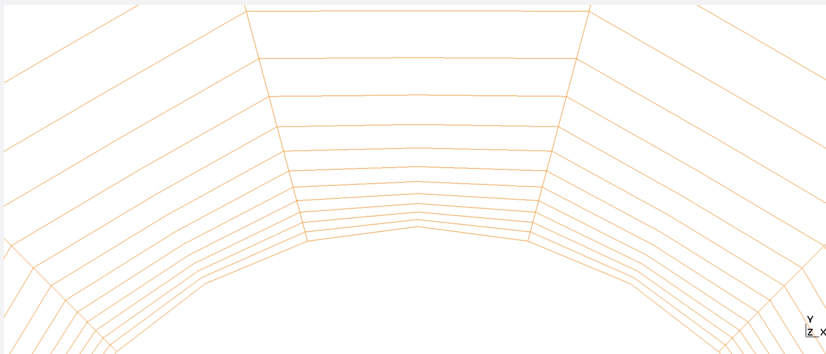
Possible L-E smoothing of P2 mesh near boundary



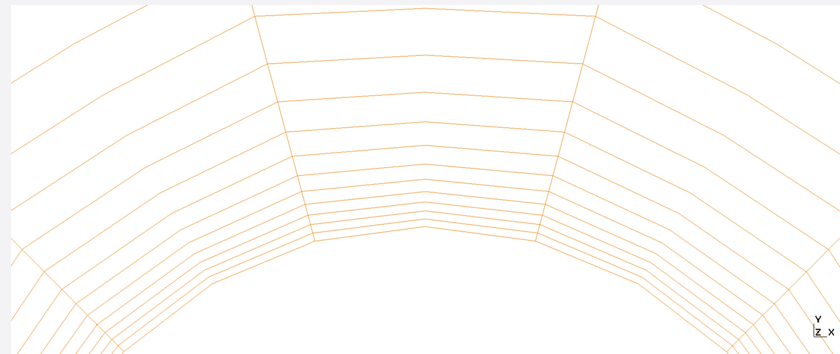
Expected result for clustered P2 mesh

Mesh Smoothing

- Shoemake is exploring the use of orthotropic material properties with L-E smoothing.
 - Idea is to make mesh stiffer in normal direction and more pliable in tangential direction.
 - Also allows for specifying the shear modulus.
- Original linear mesh had 1st layer distance of 0.01 from surface.
- Isotropic smoothing repositioned the corner nodes 0.0116 from the surface and the second mid-edge node 0.008 from the surface.
- The orthotropic results had all second layer nodes ~ 0.01 from the surface.



Isotropic L-E for P2 mesh



Orthotropic L-E for P2 mesh

Mesh Generation Kernels

- Some kernels are more amenable to parallel environments than others.
 - Tetrahedral meshing is inherently a serial operation.
 - Hexahedral volume meshing is very fast but typically does not have good parallel performance. It mostly uses parallel for increased problem size.
- Kernels where the mesh is modified should also support dynamic re-partitioning.
- Many of the kernels may (should) require access to geometry.

Towards Automated Mesh Generation

Towards Automated Mesh Generation

- NASA study describes mesh generation as a bottleneck and dominant cost in terms of human intervention.

“since a computational mesh is merely a means to enable the CFD simulation, ultimately the mesh generation process should be invisible to the CFD user or engineer.”
- So, progress must be made to automate much of the mesh generation phase of the simulation.
- Scripting is an integral component of automated mesh generation.
- Pointwise customers use scripts to automate repetitive operations. Some are so sophisticated that the entire mesh is constructed via scripts. These tend to be meshes with minor variations from a given mesh topology and strategy.

Towards Automated Mesh Generation

- The mesh generation community understands the desire to make the mesh invisible to the user.
- It is merely a statement of a desire to have a robust, fully-automated mesh generation process.
- Parts of the process can be automated now.
- Fully automated multi-block structured mesh generation has been a goal for many years, but not much progress has been made.
- Unstructured mesh generation offers the hope of automation, due to the relative ease at handling geometry complexity.

Towards Automated Mesh Generation

- If one assumes the starting point is a water-tight geometry then fully automated mesh generation is possible today, although restrictions must be imposed w.r.t. mesh topology and spacing.
 1. Input geometry can be subdivided into logical patches based on features.
 2. Patch boundaries can be automatically discretized using equally-spaced points.
 3. Closed loops of boundary edges can be tessellated with triangles.
 4. These triangulate patches can be assembled into a unstructured block.
 5. The block can be initialized using a Delaunay method.
- All could have been done without human intervention.
- The starting point was **geometry!**

Towards Automated Mesh Generation

- Was the mesh produced what the user wanted?
Probably not. It is a basic isotropic tetrahedral mesh.
- Pointwise will begin to explore intelligent automation in collaboration with MIT and Syracuse University.
 - Geometry created in ESP will be attributed with mesh-centric information that can include meta data, such as labels like “Wall” or “Symmetry”, and scalar information such as desired normal and tangential spacing.
 - Pointwise will import the geometry from ESP, along with the attribution data.
 - Glyph scripts will be developed to interpret the attributed information and modify the default behavior.
 - Each additional piece of attributed data will be a clue to the automation process.
 - The more clues, the more the result will resemble the user’s intent.

Conclusions

Conclusions

- The NASA CFD Vision 2030 study is an important document that provides focus for research into the CFD process and the mesh generation process.
- Several areas important to the process were presented. Some Pointwise specific research was included.
 1. Geode Core nearing public beta
 2. High Order Mesh Curving in future release
 3. Adaptation strategy evolving. (Work with FUN3D in AIAA-2017-3109, mesh/solver communication part of NASA SBIR recently selected for award)
 4. Automated meshing scripts to be developed with MIT/Syracuse under Air Force contract (CAPS).
 5. High-Order visualization under Intelligent Light contract with DOE.

Conclusions

- More research is needed as we collectively work toward the goals of the study.
- Geometry is or will become important to all aspects of the CFD process, therefore it should be persistent.
 - It starts the process by providing the shape.
 - It is needed for adaptation, high order elevation and shape design.
 - It could be attributed with additional information for automating the process.

Conclusions

- Commercial mesh generation vendors offer tools that provide value to the engineering process for customers.
- The NASA study poses challenges to researchers throughout: government labs, academia and industry.
- Investments made by commercial vendors should be aligned with research funding in academia and government.
- The challenges are too great for one group to solve in isolation.
- Collaborative efforts will accelerate the progress toward automated, intelligent mesh generation.